NREL
NATIONAL RENEWABLE ENERGY LABORATORY

System Advisor Model Introduction

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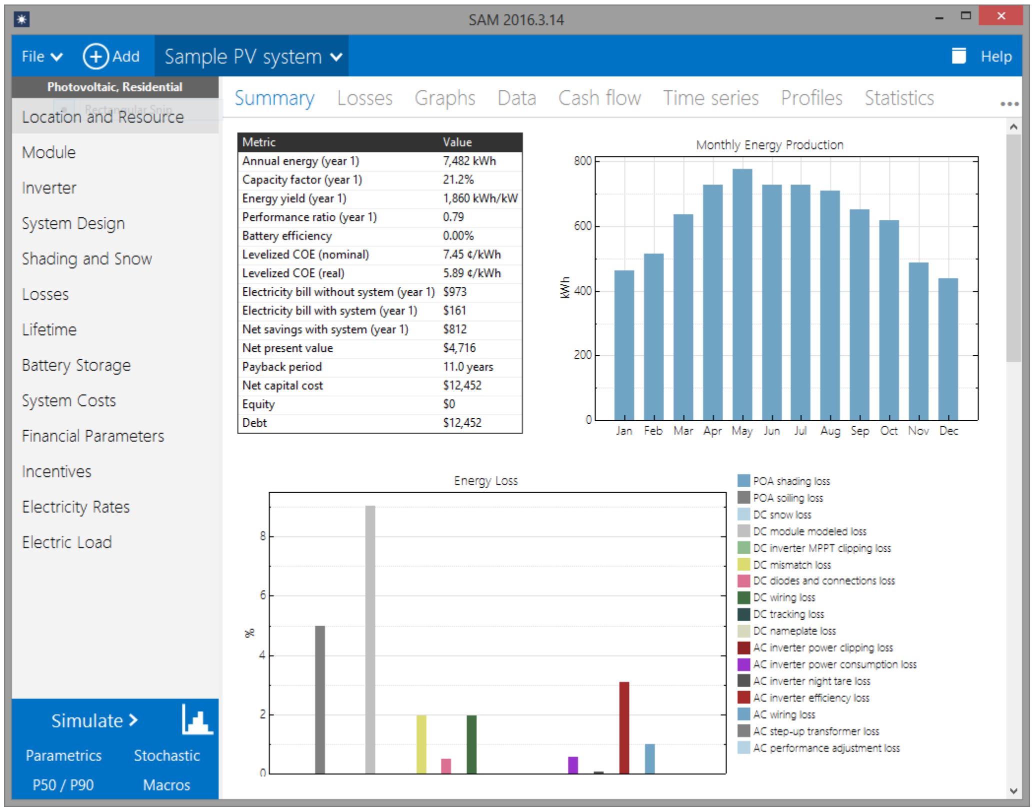
SunShot U.S. Department of Energy

Outline

- SAM Introduction
- Photovoltaic Model
- Battery Model

System Advisor Model (SAM)

Free software that combines detailed performance and financial models to estimate the cost of energy for systems



http://sam.nrel.gov/download

Technologies

Photovoltaics, detailed & PVWatts
Battery storage
Concentrating solar power
Wind
Geothermal
Biomass
Solar water heating

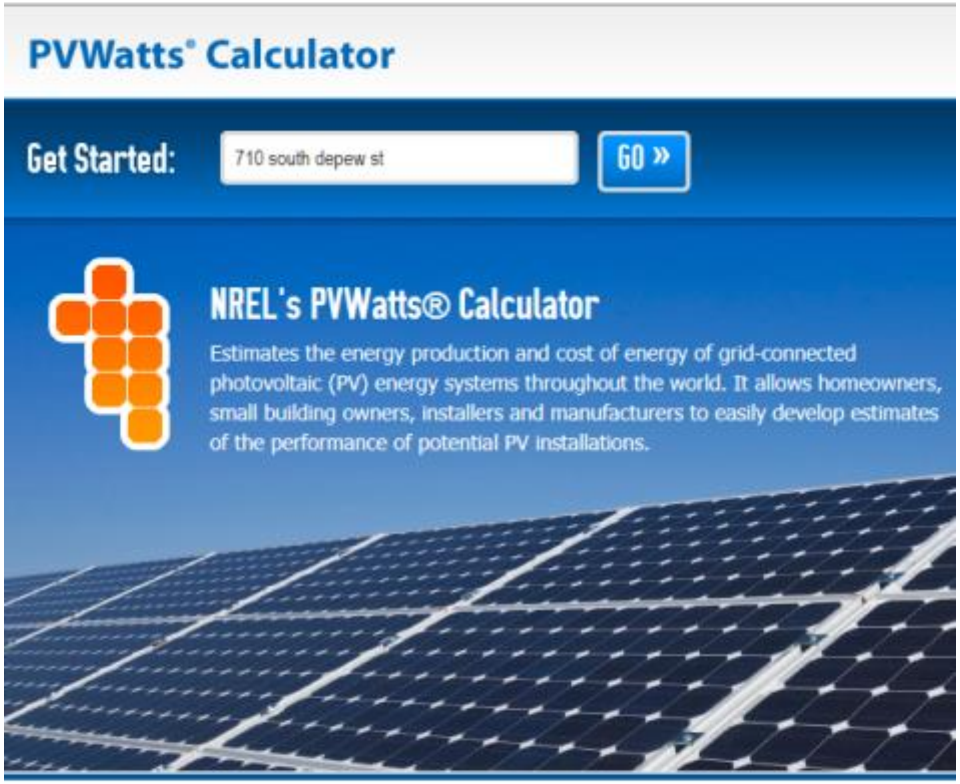
Financials

Behind-the-meter
- residential
- commercial

Power purchase agreements
- single owner
- equity flips
- sale-leaseback

Simple LCOE calculator

PVWatts or SAM?



*The SAM team maintains the PVWatts model, and it's included with SAM.

PVWatts

- Provides a simple performance and financial assessment for smaller-scale PV systems given an address, system design, and simple $/kWh electricity rate.

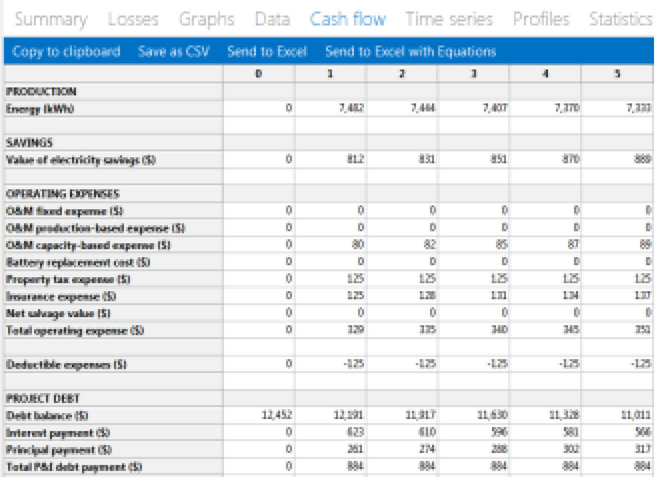
SAM

- Provides detailed performance assessment for small to utility scale systems
- Model complex shading and other losses.
- Can model detailed financial parameters, including complex utility rate tariffs, incentives.
- Models custom load profiles.
- Detailed outputs and visualization

Questions you can answer with SAM

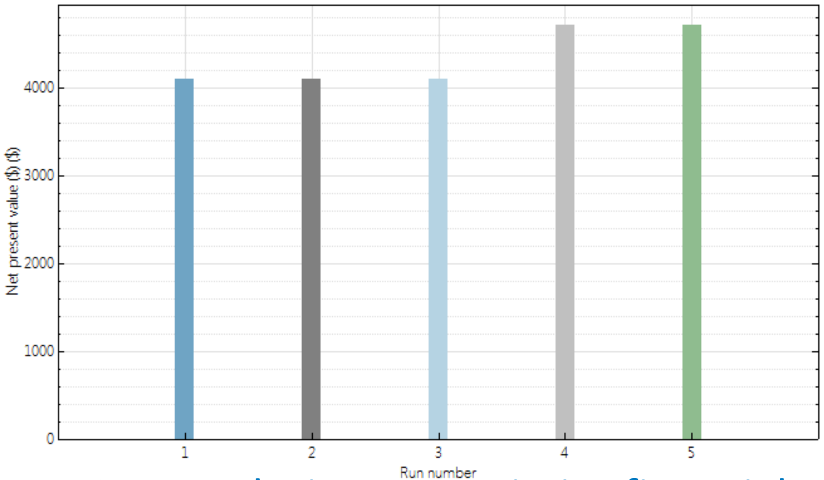
Metric	Value
Annual energy (year 1)	7,482 kWh
Capacity factor (year 1)	21.2%
Energy yield (year 1)	1,860 kWh/kW
Performance ratio (year 1)	0.79
Battery efficiency	0.00%
Levelized COE (nominal)	7.45 ¢/kWh
Levelized COE (real)	5.89 ¢/kWh
Electricity bill without system (year 1)	$973
Electricity bill with system (year 1)	$161
Net savings with system (year 1)	$812
Net present value	$4,716
Payback period	11.0 years
Net capital cost	$12,452
Equity	$0
Debt	$12,452

- Predicted technical and financial performance over project lifetime

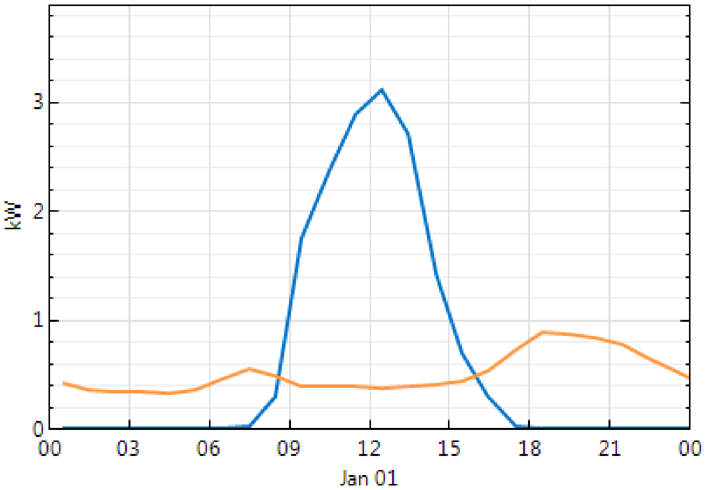


	0	1	2	3	4	5
PRODUCTION						
Energy (kWh)	0	7,482	7,444	7,407	7,370	7,333
SAVINGS						
Value of electricity savings ($)	0	812	831	851	870	889
OPERATING EXPENSES						
O&M fixed expense ($)	0	0	0	0	0	0
O&M production-based expense ($)	0	0	0	0	0	0
O&M capacity-based expense ($)	0	80	82	85	87	89
Battery replacement cost ($)	0	0	0	0	0	0
Property tax expense ($)	0	125	125	125	125	125
Insurance expense ($)	0	125	128	131	134	137
Net salvage value ($)	0	0	0	0	0	0
Total operating expense ($)	0	329	335	340	345	351
Deductible expenses ($)	0	-125	-125	-125	-125	-125
PROJECT DEBT						
Debt balance ($)	12,452	12,191	11,917	11,630	11,328	11,011
Interest payment ($)	0	623	610	596	581	566
Principal payment ($)	0	261	274	288	302	317
Total P&I debt payment ($)	0	884	884	884	884	884

- Detailed cash-flow financials



- System design to maximize financial return



- Time series behavior of system performance

Detailed photovoltaic model

Irradiance
- Transposition using Isotropic, HDKR, or Perez
- Measured plane of array (POA) input

Shading
- Irregular obstruction shading from 3D scene
- Self-shading for regularly spaced rows
- External input from SunEye, Solar Pathfinder
- Snow cover loss model

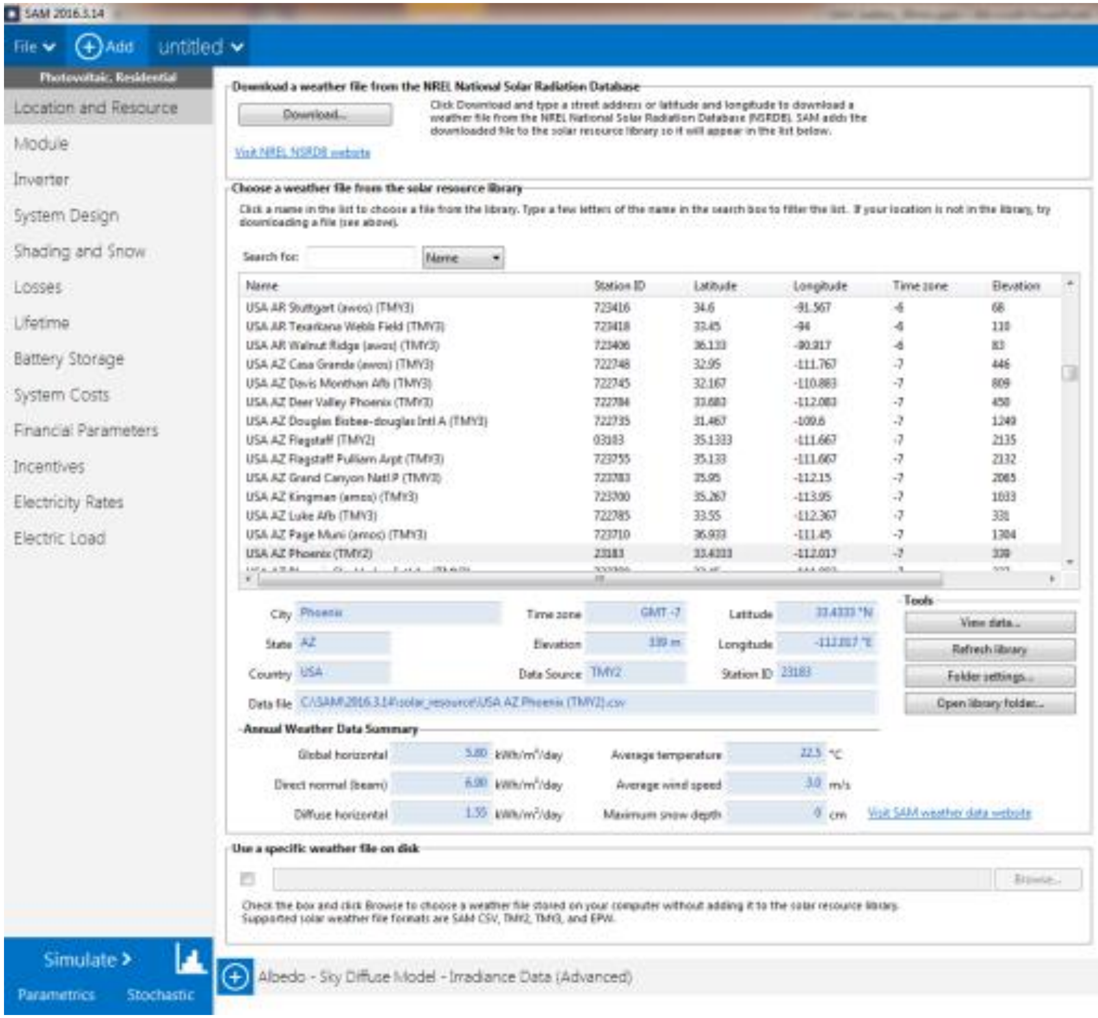
Module
- Simple efficiency model
- Single diode model (CEC database or datasheet)
- Extended single diode model (for IEC-61853 tests)
- Sandia PV Array Performance Model

Inverter
- Sandia/CEC grid-tied inverter model
- Datasheet part-load efficiency curve

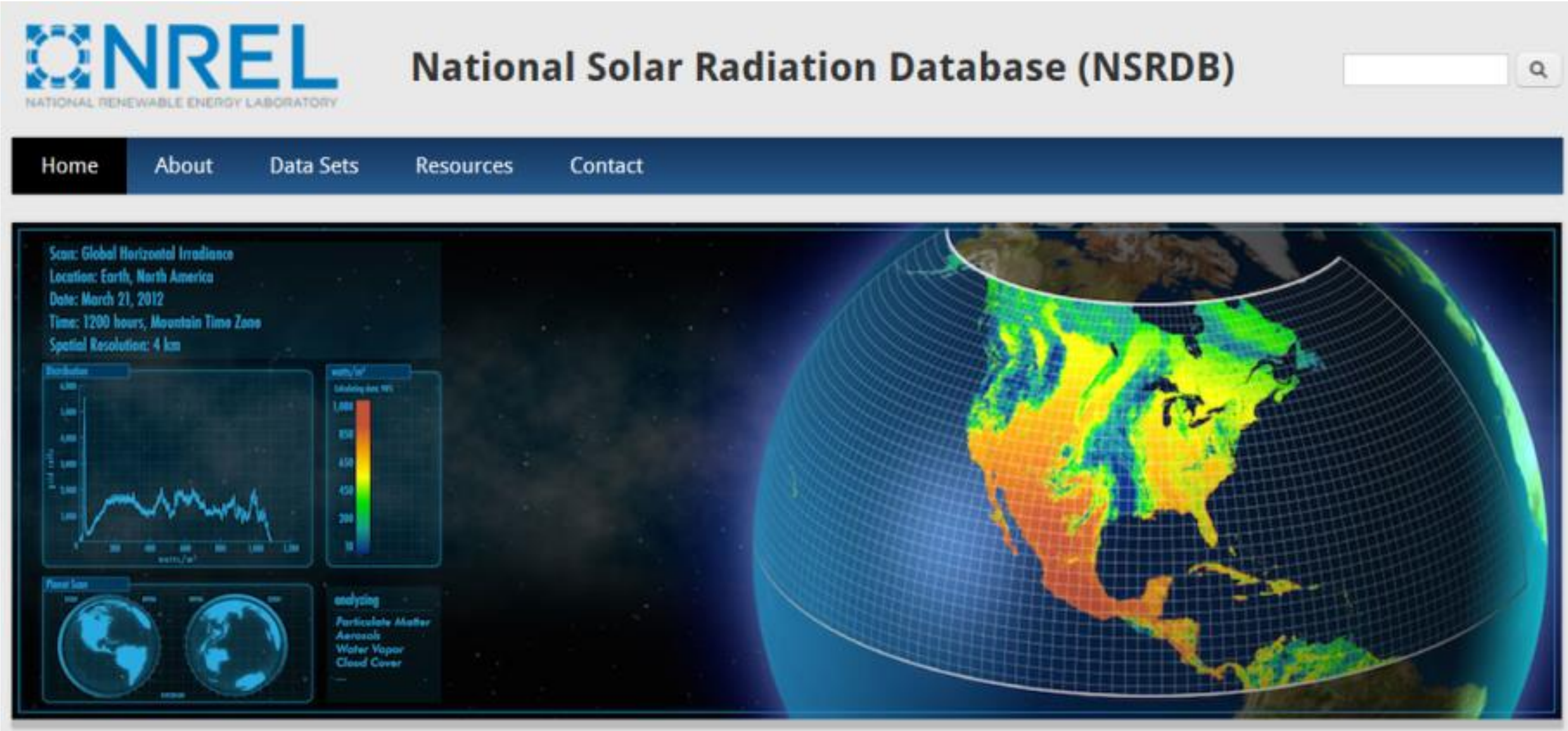
System
- Sizing wizard or electrical layout
- Multiple subarrays
- Fixed, 1 axis, backtracking, azimuth axis, 2 axis
- Battery storage

Degradation
- Extrapolated single year
- Lifetime simulation of all years

Simulation
- 1 minute to 1 hour time steps

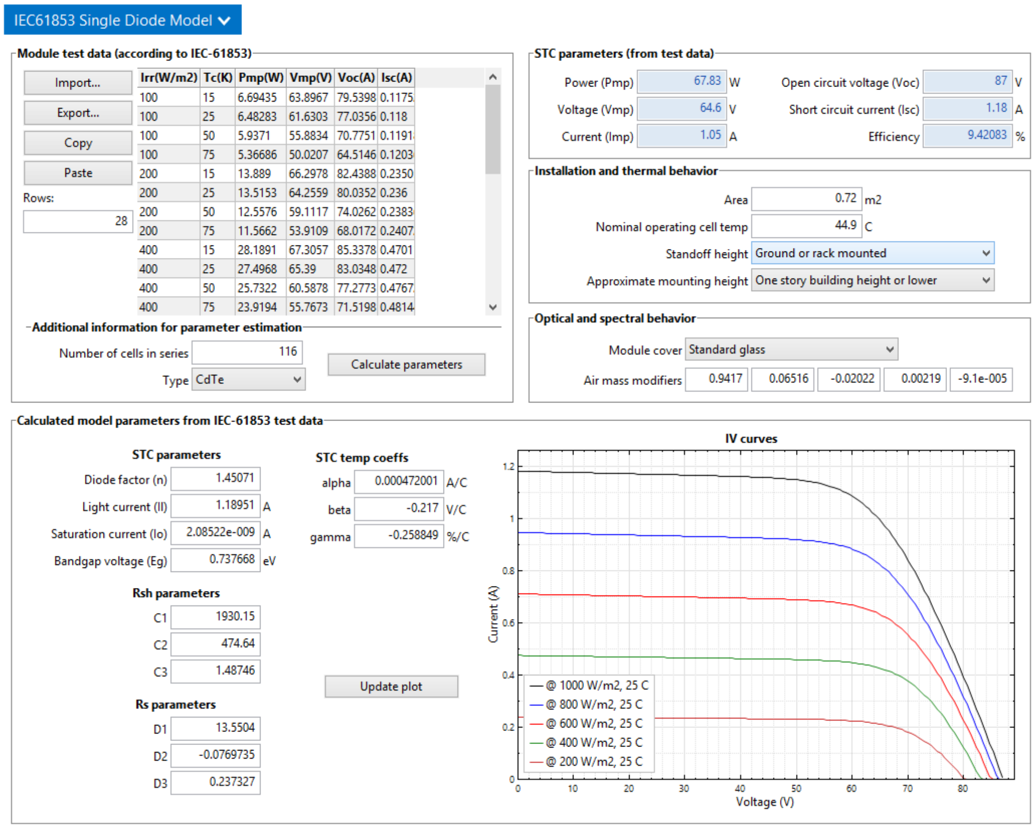


Resource Data



- SAM allows selection from NREL NSRDB, TMY3, or input of a custom user defined weather file in an easy to use format.
- Multiple sources of data available: sam.nrel.gov/weather
- NSRDB – 4x4 km data at 30 minute resolution for North and Central America. 10x10 km hourly data for various countries in South Asia

Module and Inverter Modeling

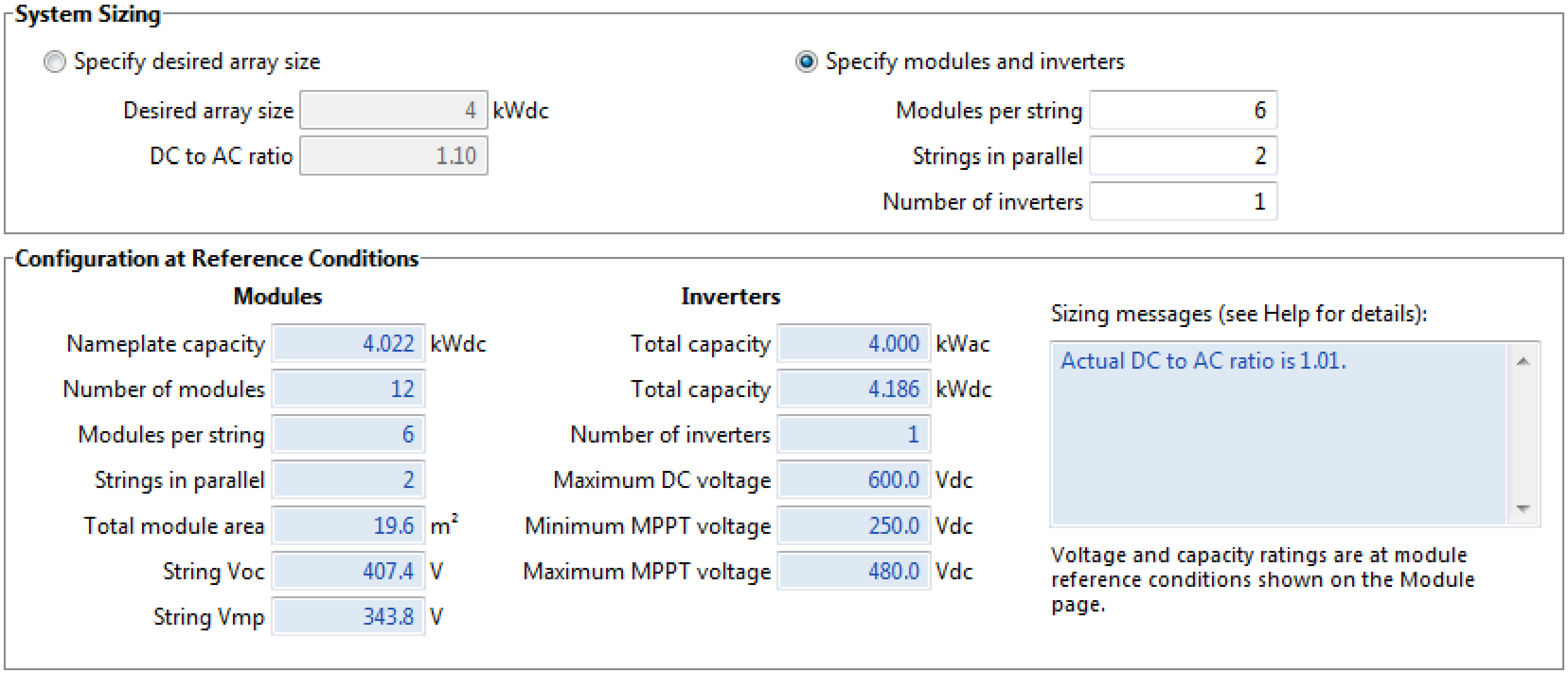


Can choose which performance model to use (Simple, CEC, Sandia, IEC-61853)

Select module and inverter from a database maintained by the California Energy Commission or specify your own parameters from a datasheet or part load curve.

Dobos, A.; MacAlpine, S. Procedure for Applying IEC-61853 Test Data to a Single Diode Model. Proc. IEEE 40th PVSC Conf. Denver CO, June, 2014

Auto size the system or specify the module strings and inverters directly.



Configure up to 4 sub-arrays, each with a specific:

- Tracking system
- Tilt
- Azimuth
- Ground Coverage Ratio
- Shading Table

3D shading calculator

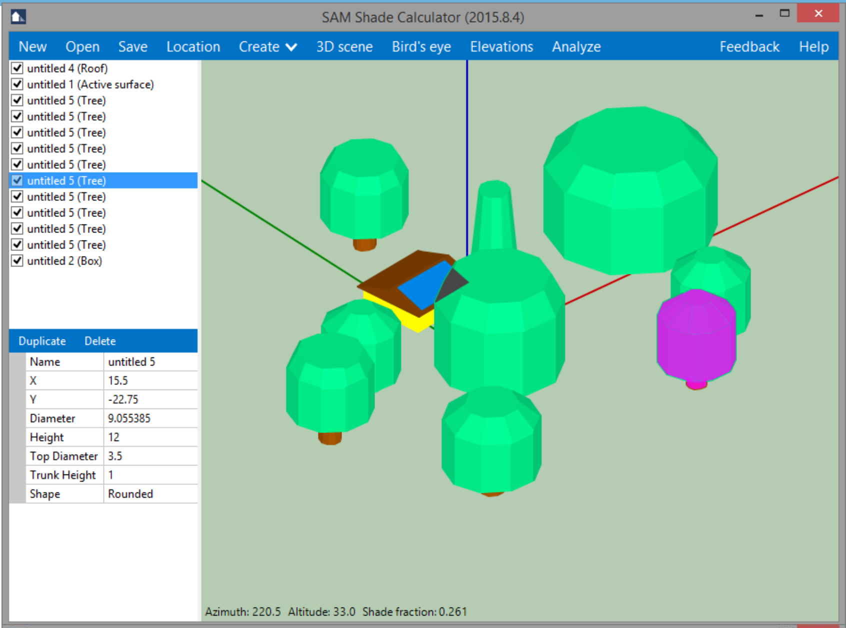
Calculates linear beam irradiance shading losses and sky diffuse view factor loss

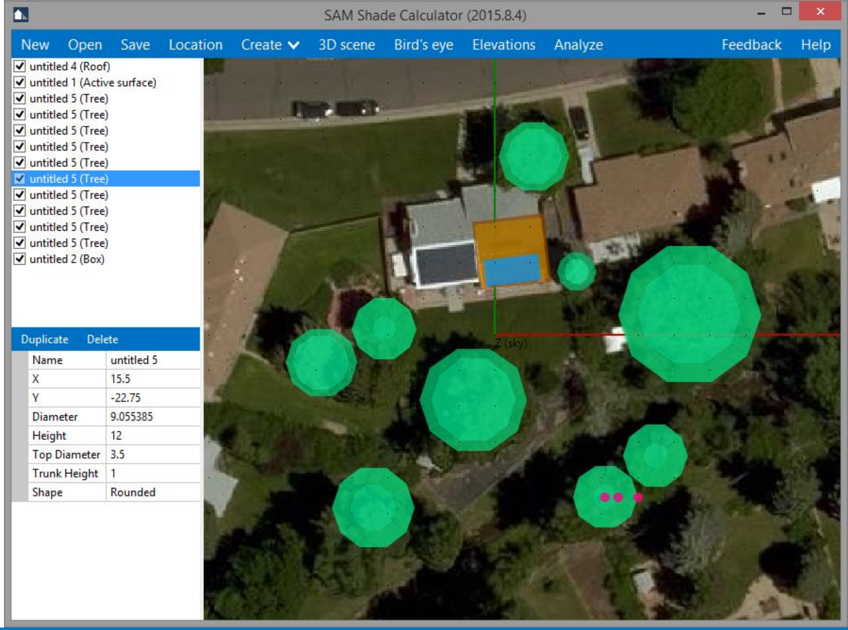
Imports 2D mapping underlays from online maps

Outputs are diurnal or hourly/subhourly time series linear shade loss percentages

You can group PV surfaces into subarrays and specify parallel strings

Scripting to automate panel layout and import/export geometry data





Loss Modeling

- Irradiance Losses
  - Soiling
- DC Losses
  - Module mismatch
  - Wiring
  - Diodes and connections
- AC Losses
  - Wiring
  - Transformer

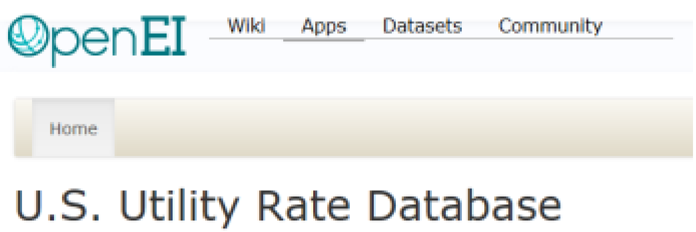
Financial Modeling

Financial models:

Residential (distributed) Commercial (distributed)	• Specify electric load • Specify utility rate structure
Third party ownership	• From perspective of off-taker (customer)
PPA single owner (utility) PPA partnership flip with debt (utility) PPA partnership flip without debt (utility) PPA sale leaseback (utility)	• Utility scale systems with various ownership structures • Power purchase agreements specify value of selling power to grid throughout the year
LCOE calculator (FCR method)	• Non cash-flow based fixed-charge rate method for calculating LCOE. • Best for market level (not project level) analysis.
No financial model	• If you are only interested in system performance, not financial performance

All financial calculations generally require some information about system costs, loans, taxes, inflation rates, discount rates, depreciation, and other relevant parameters, depending on the model

Complex Utility Rate Tariffs



Weekday

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	4	4	4	4	4
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Jul	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	2	2	2	2	2
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Dec	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	4	4	4	4	4

Rate Structure for Energy Rates

Import... Export... Copy Paste

Period	Tier	Max. Usage	Max. Usage Units	Buy ($/kWh)	Sell ($/kWh)
1	1	1e+038	kWh	0.26687	0.26687
2	1	1e+038	kWh	0.08328	0.08328
3	1	1e+038	kWh	0.22057	0.22057
4	1	1e+038	kWh	0.08326	0.08326

Number of entries: 4

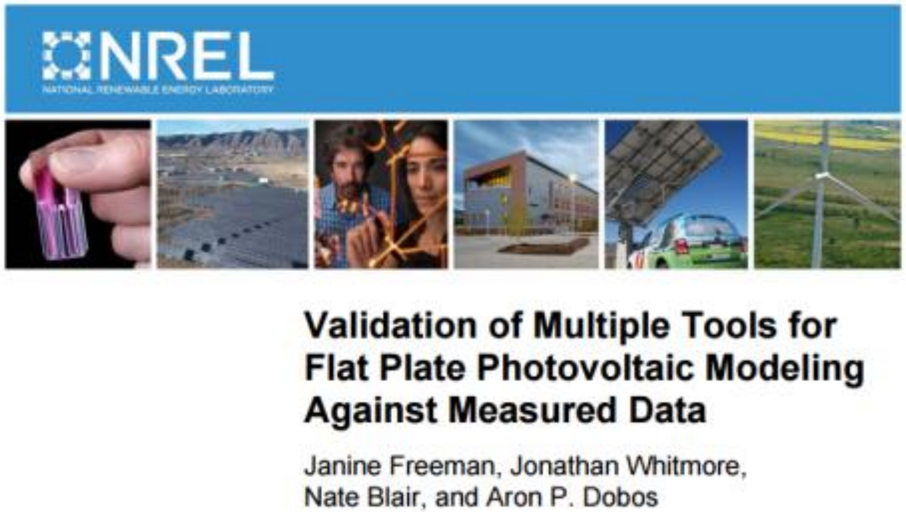
Utility Rate Database

- Tool in SAM to download and automatically populate complex inputs from utility rate database.
- http://en.openei.org/apps/USURDB/

Modeling

- Time-of-use energy and demand charges with ability to model usage tiers.
- Monthly demand charges
- Multiple metering and rollover options
- Convenient output of energy/demand charges by month, period, tier, etc.

Validation Studies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Validation of Multiple Tools for Flat Plate Photovoltaic Modeling Against Measured Data

Janine Freeman, Jonathan Whitmore, Nate Blair, and Aron P. Dobos

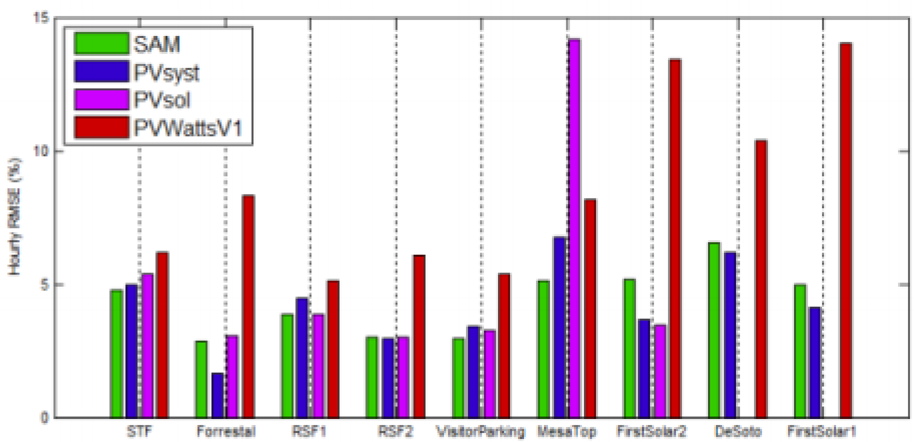


Figure 3. Normalized hourly RMSE of each tool, sorted in order of system size [1]

Photovoltaic Modeling

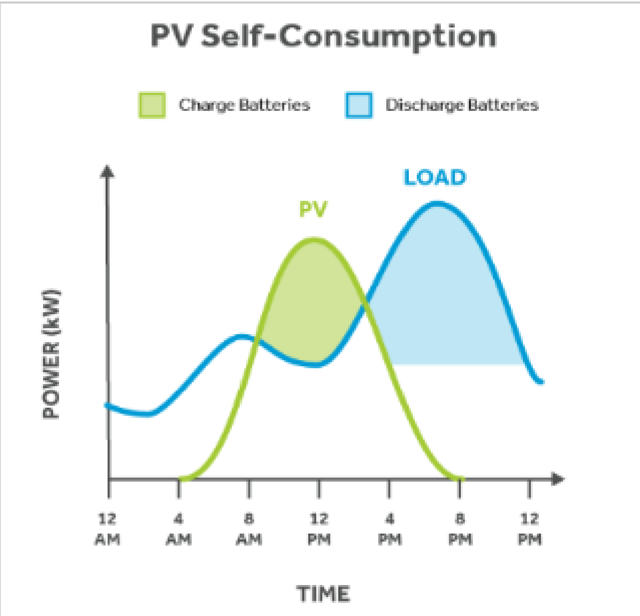
- Comparisons of SAM and other tools to measured performance data:
- Most recent study concluded SAM annual errors within +/- 8% of measured data
- https://sam.nrel.gov/case-studies

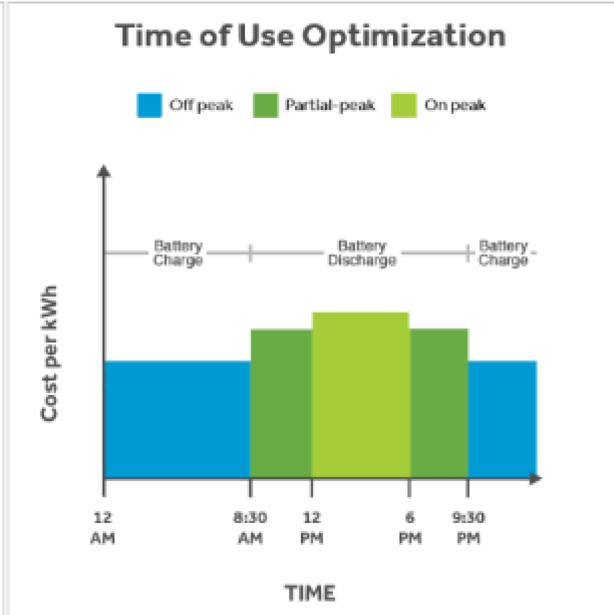
Upcoming Validation

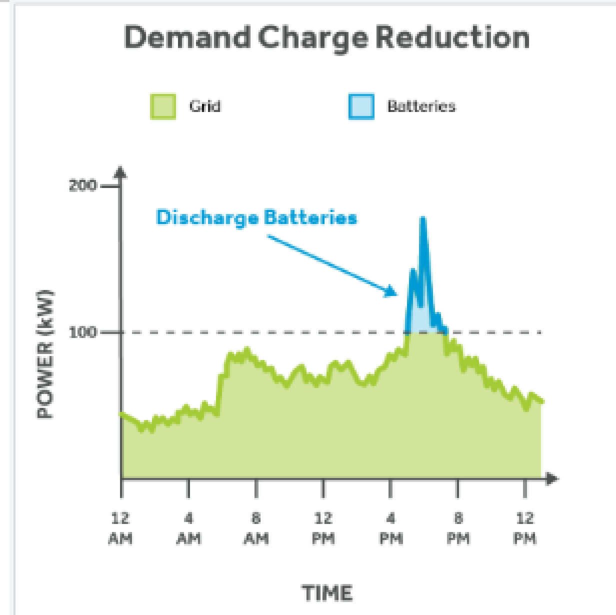
- Comparison of SAM and other tools 3D shading calculations against SunEye measurements.
- Preliminary results suggest potentially large differences between tools

SAM Battery Model

Motivation for behind-the-meter storage







Images from: http://www.aquionenergy.com/

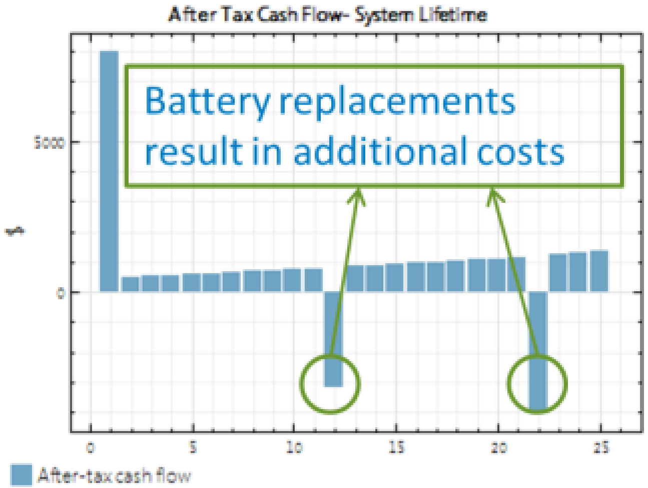
- Batteries charged primarily from PV eligible for Federal ITC subject to 75% cliff
- End of NEM in some states

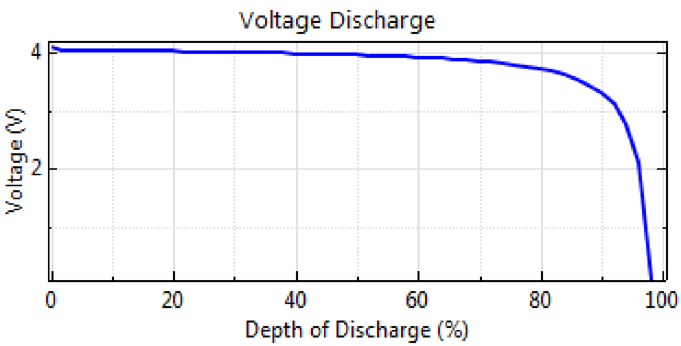
- Residential and commercial utility rate structures with high TOU charges.
- Charge when rate is low, discharge when rate is high

- Commercial utility structures can have very high TOU demand charges.

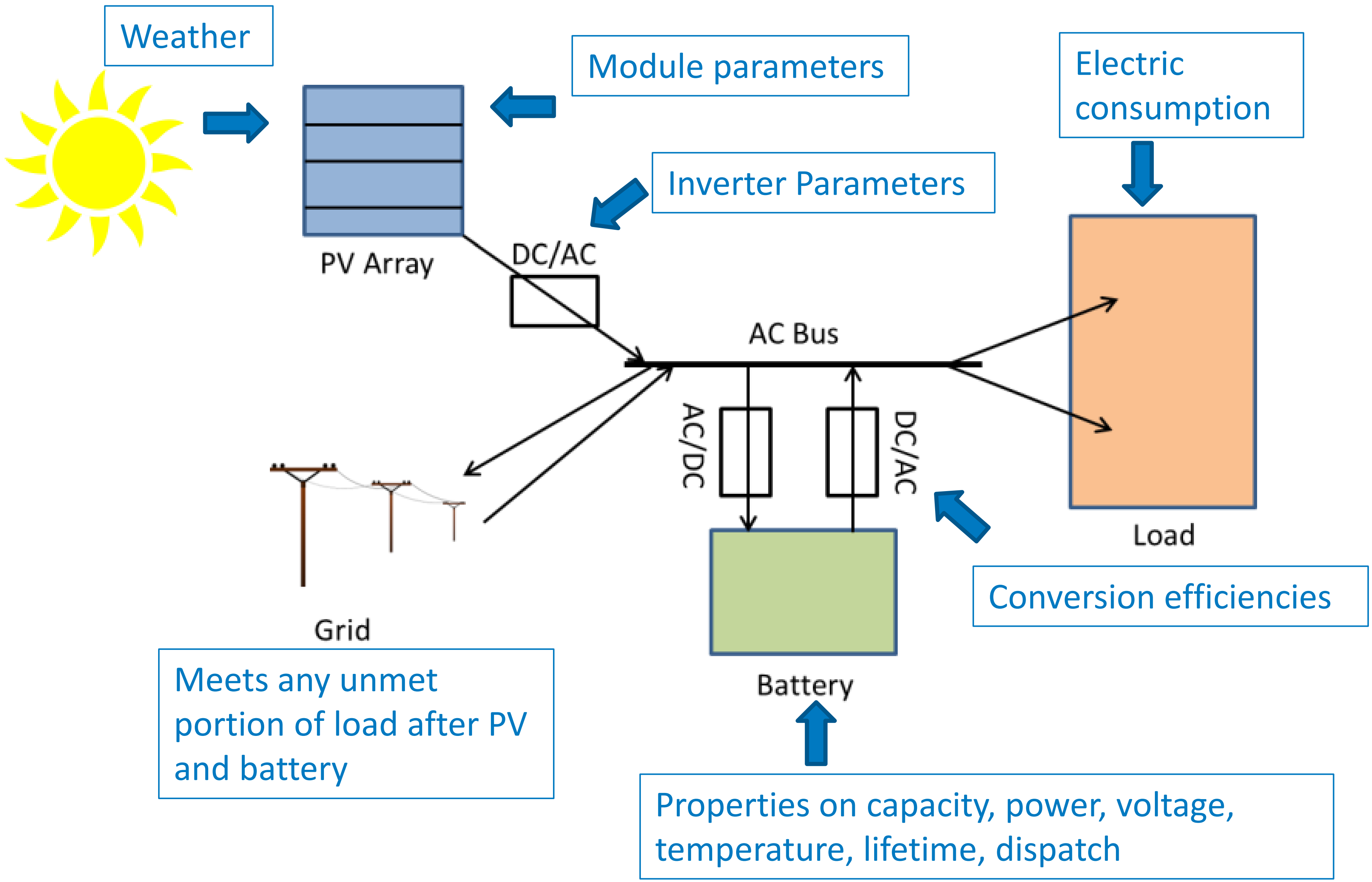
Model Overview

- Techno-economic model for residential, commercial, and third-party ownership systems
  - Lead acid & lithium ion battery chemistries
  - System lifetime analysis including battery replacement costs
  - Models for terminal voltage, capacity, temperature
  - Multiple dispatch controllers available

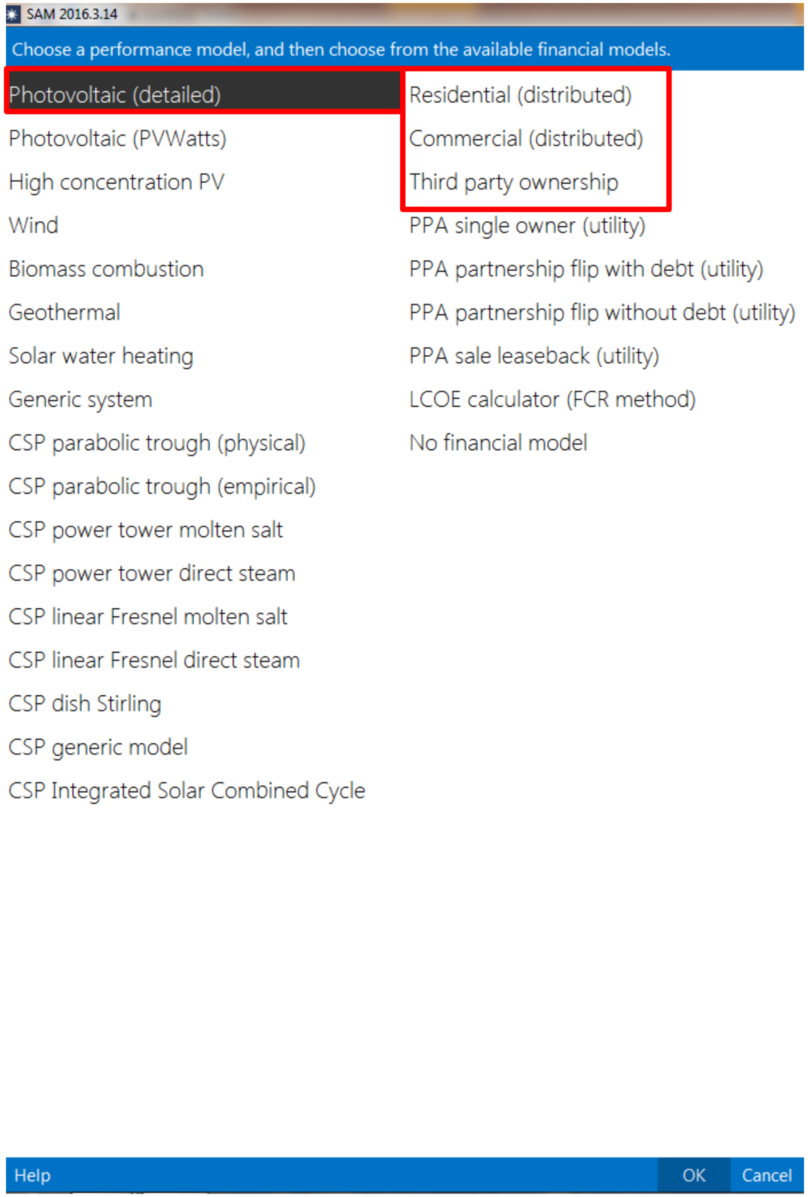


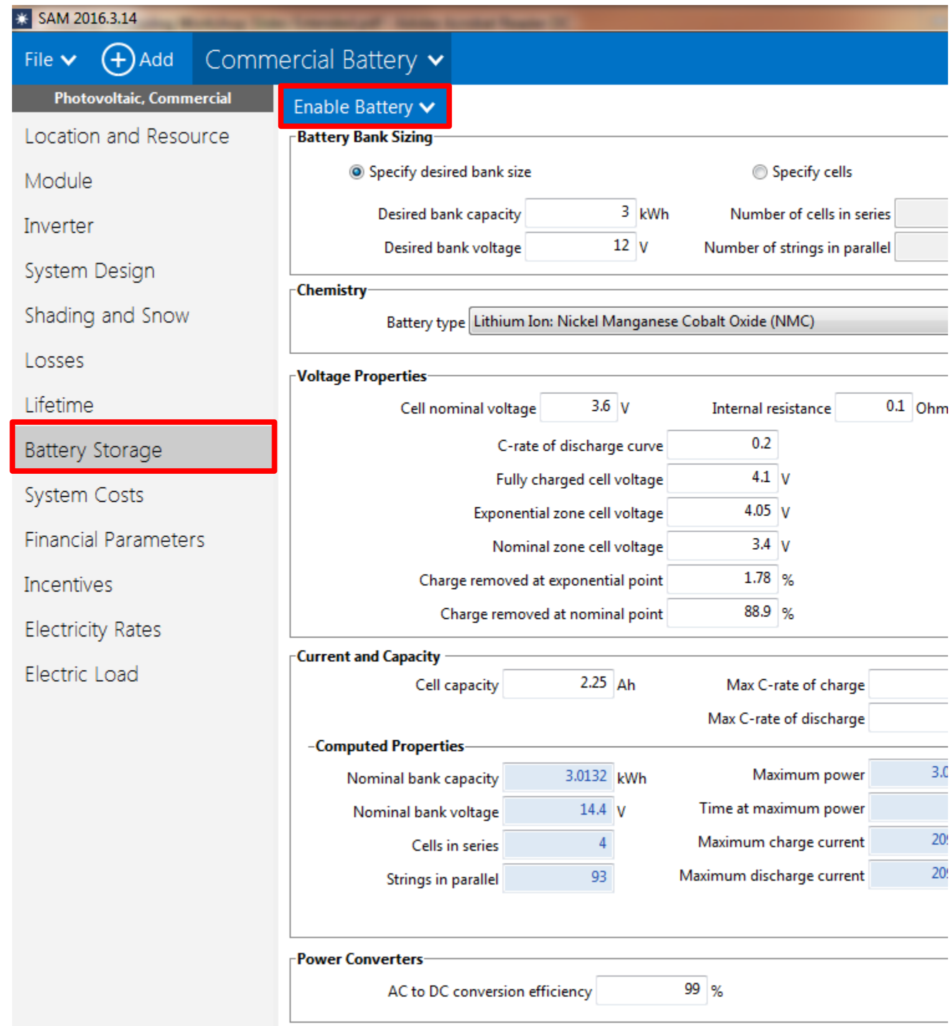


Modeled Configuration



Implementation in SAM





Battery Financials

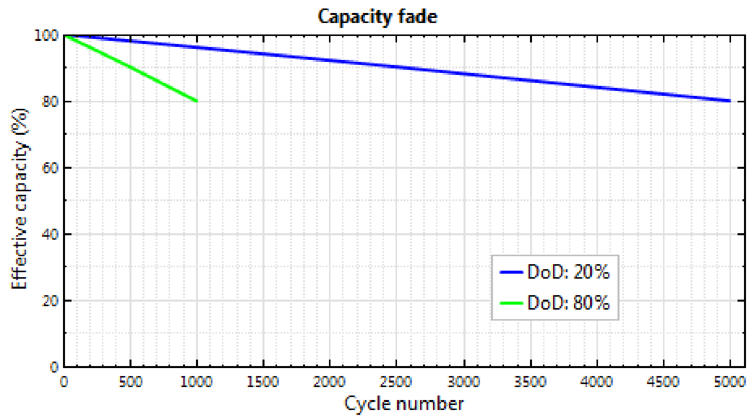
- **Lifetime**

PV simulation over analysis period

PV Array Performance Degradation

Module degradation rate Value Sched 0 %/year

Applies to the array's hourly DC output.



Battery capacity fades with cycling, depends on depth-of-discharge

- **System Costs**

Direct Capital Costs

Module	928	units	0.2	kWdc/unit	199.8	kWdc	0.71	$/Wdc
Inverter	5	units	36.0	kWac/unit	180.0	kWac	0.21	$/Wdc
				Battery bank	3.0	kWh dc	600.00	$/kWh dc

- **Battery Bank Replacement (Battery Storage page)**

Battery Bank Replacement

- No replacements
- Replace at specified capacity
- Replace at specified schedule

Battery bank replacement threshold 20 % capacity

Battery bank replacement schedule Edit data...

Battery bank replacement cost 600 $/kWh

Battery cost escalation above inflation 0 % %/year

SAM applies both inflation and escalation to the first year cost to calculate out-year costs. See Help for details.

Battery Dispatch

Storage Dispatch Controller

Choose Dispatch Model

- ( ) Peak shaving: 1-day look ahead
- ( ) Peak shaving: 1-day look behind
- ( ) Automated grid power target
- (•) Manual dispatch

Charge Limits and Priority

Minimum state of charge	30	%
Maximum state of charge	95	%
Minimum time at charge state	10	min

Automated Grid Power Target Model

Enter single or monthly powers

Single or monthly [Edit values...] kW

Time series [Edit data...] kW

Manual Dispatch Model

	Charge from PV	Charge from grid: Allow	Charge from grid: % capacity	Discharge: Allow	Discharge: % capacity
Period 1:	☑	☐	25	☐	25
Period 2:	☑	☑	25	☐	25
Period 3:	☑	☐	25	☑	25
Period 4:	☐	☐	25	☐	25
Period 5:	☐	☐	25	☐	25
Period 6:	☐	☐	25	☐	25

To activate the manual dispatch model, choose Manual Dispatch under "Choose Dispatch Model" above. These inputs are inactive for the automated dispatch options.

The manual dispatch model aims to minimize purchases from the grid. It first tries to meet load with PV, then battery, then grid. Choose whether PV should meet the load or charge the battery below. Use the timing controls to constrain the battery controller. See help for details.

- (•) PV meets load before charging battery
- ( ) PV charges battery before meeting load

Weekday

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
Jan	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
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Dec	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1

Weekend

	12am	1am	2am	3am	4am	5am	6am	7am	8am	9am	10am	11am	12pm	1pm	2pm	3pm	4pm	5pm	6pm	7pm	8pm	9pm	10pm	11pm
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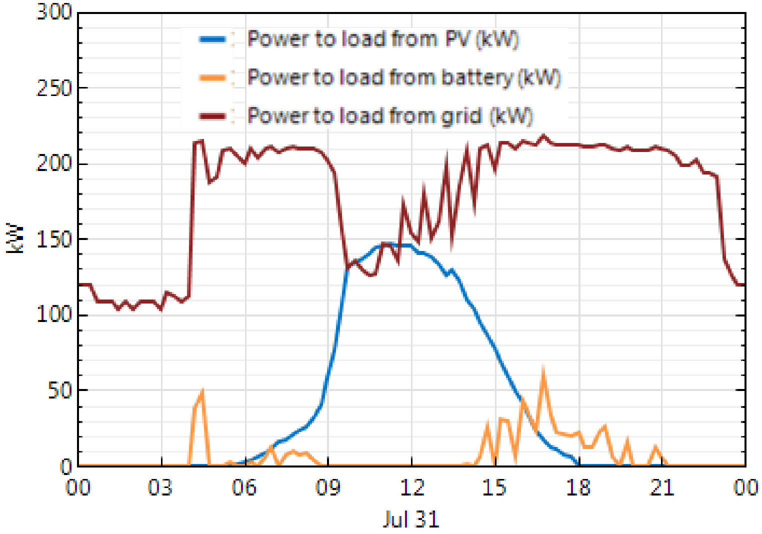
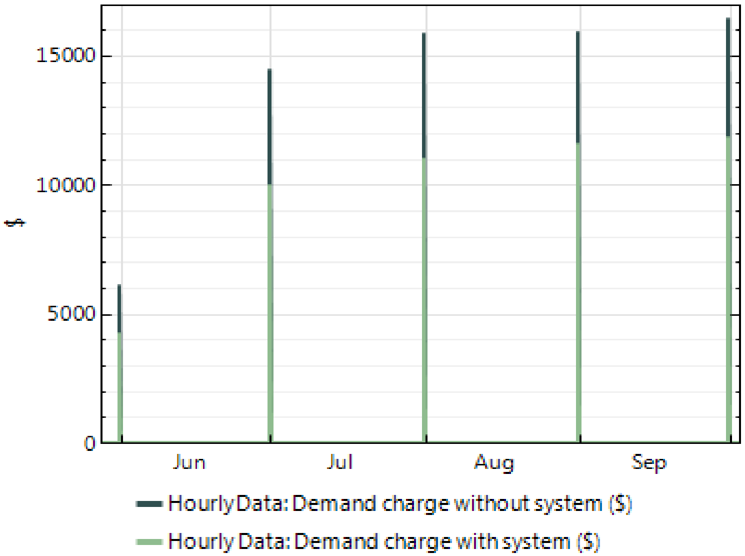
Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

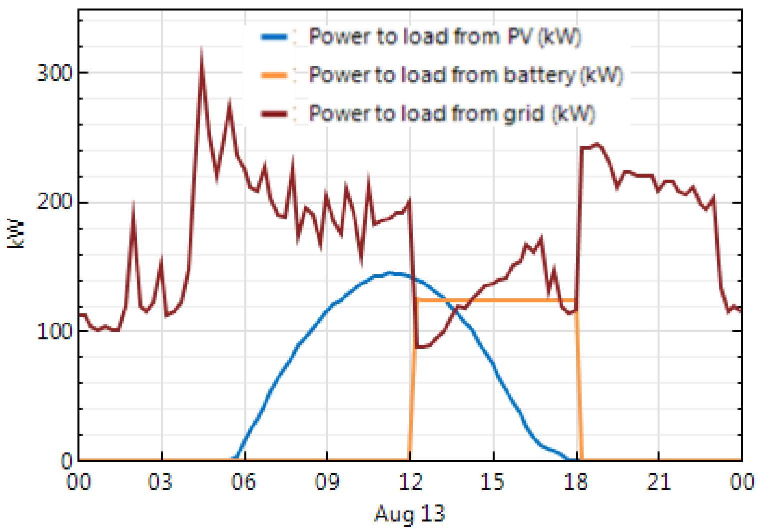
Dispatch Visualization

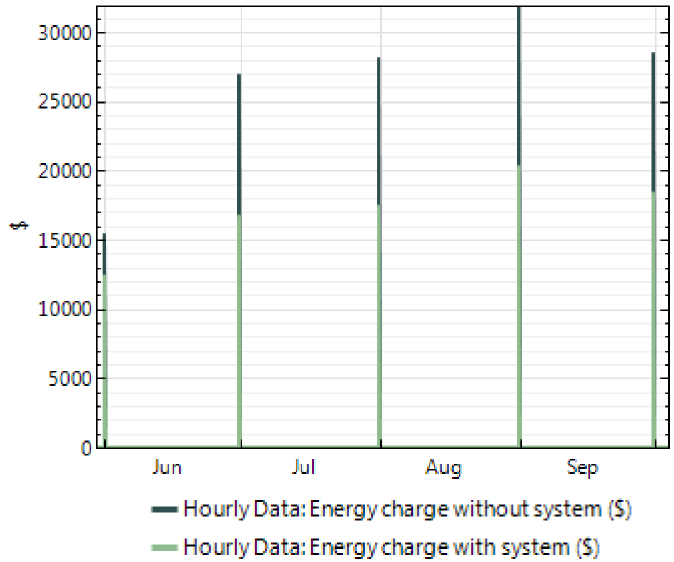
Peak shaving for demand charge reduction





Manual dispatch for energy arbitrage





Example Case Study

- Evaluate economics of installing PV-coupled battery system for demand-charge reduction:
  - Los Angeles, CA
  - 27,625 ft^2 grocery store with 247 kW peak load
  - Southern California Edison TOU-GS-2 Option B

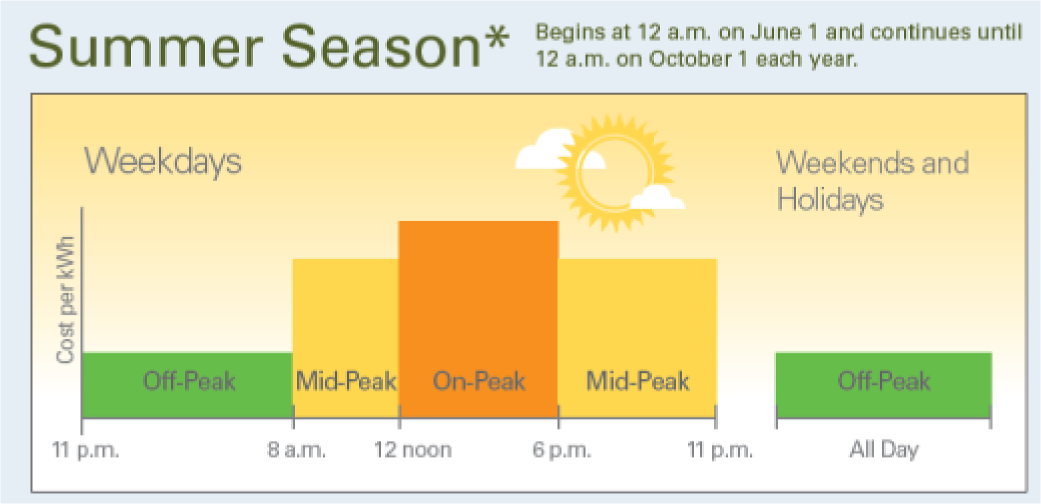
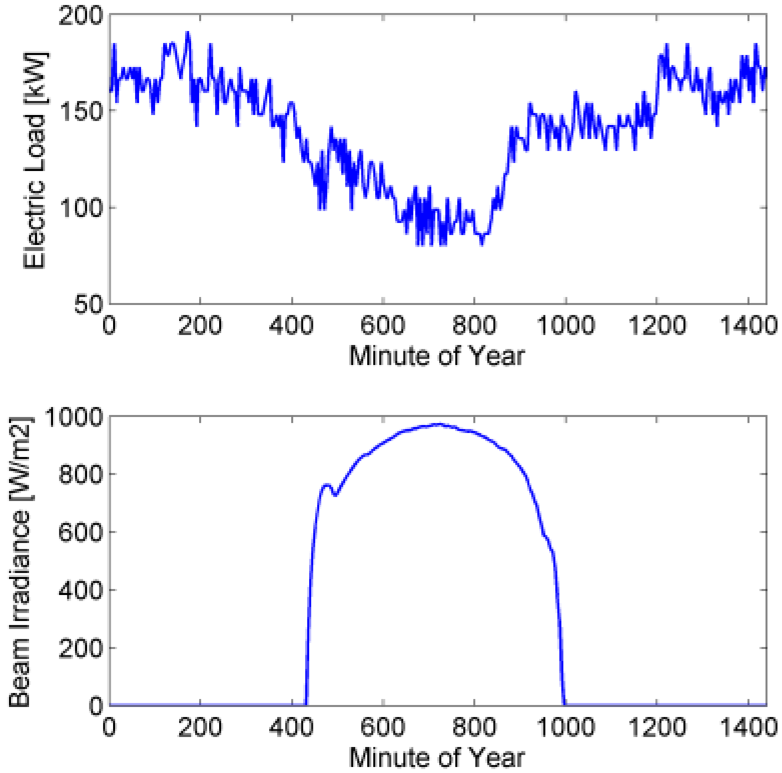


Image from SCE TOU-GS-2 Option B datasheet

Simulation Data

- One-minute weather data taken from NREL's Measurement & Instrumentation Data Center network, location in Los Angeles.
- Five-minute electric load data obtained from EnerNOC's free online database for commercial facilities.
- Assumed California's SGIP applied

January 1st, 2012



Lithium Ion Battery System

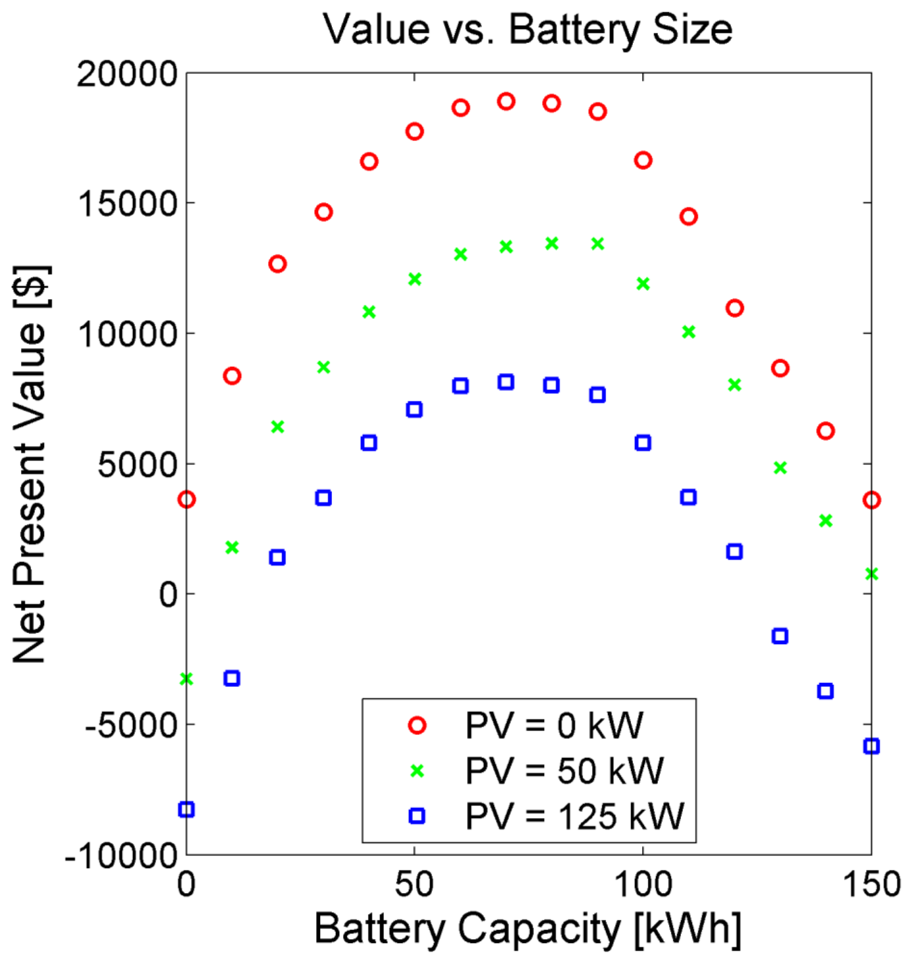
- Model battery similar to Tesla Powerwall
  - Lithium-ion nickel manganese cobalt
  - Assumed can cycle full 7 kWh down to 30% of state-of-charge, for a full capacity of 10 kWh.
  - Price given as ~$300/kWh before balance of system costs.
  - Assumed lifetime of 10-15 years before degrading to 70% of original capacity

Table 3: Tesla Powerwall Specifications [13]

Property	Value
Price	$3000
Capacity	7 kWh
Power	2.0 kW continuous, 3.3 kW peak
Efficiency	92%
Voltage	350 – 450 V
Current	5.8 A nominal, 8.6 A peak
Weight	100 kg
Dimensions	1300 mm x 860 mm x 180 mm

Image from teslamotors.com/powerwall

Parametric sizing results

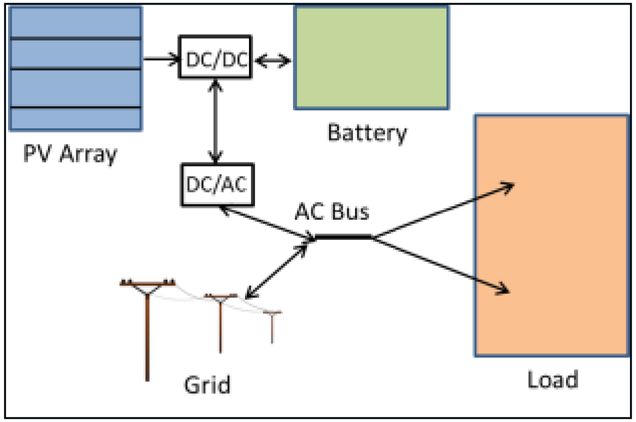


- NPV maximized for no PV system, battery bank capacity of 70 kWh
- Illustrates simulation-based method to approximate ‘optimal’ sizing.

Upcoming features

- Additional system configurations
- Additional battery chemistries
- Battery systems for PPA financial models
- Continued improvement of dispatch controllers
- Improved lifetime modeling for some battery chemistries

DC-connected battery



Flow batteries

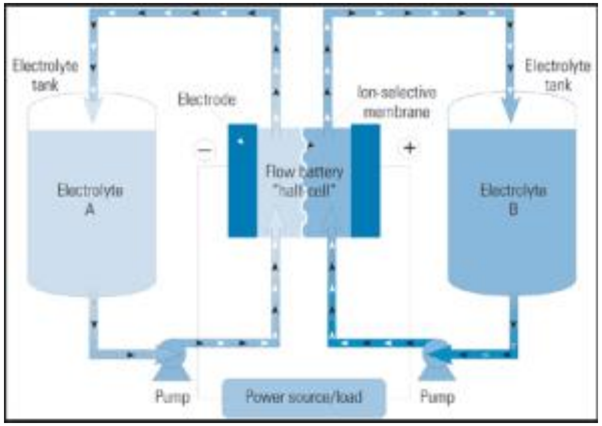


Image from tantaline.com

Battery summary

- Battery model adds on to SAM's powerful PV and inverter modeling capabilities to evaluate behind-the-meter storage systems.
- Can answer questions like:
  - What sizes of battery/PV system will provide value over the system lifetime?
  - How will battery replacement costs affect economic viability?
  - How does the dispatch strategy affect bill savings?

Questions?

- Resources:
  - **https://sam.nrel.gov/learning**
  - **https://sam.nrel.gov/videos**
  - **https://sam.nrel.gov/webinars**
- Reports available
  - Economic Analysis Case Studies of Battery Energy Storage with SAM
    - **http://www.nrel.gov/docs/fy16osti/64987.pdf**
  - Technoeconomic Modeling of Battery Energy Storage in SAM
    - **http://www.nrel.gov/docs/fy15osti/64641.pdf**

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